Demonstration of a Broadband Photon-Number Resolving Detector

Aaron J. Miller,* Sae Woo Nam, and John M. Martinis
National Institute of Standards and Technology
325 Broadway, Boulder, Colorado 80305†

Alexander V. Sergienko
Quantum Imaging Laboratory, Boston University
8 Saint Mary's Street, Boston, Massachusetts 02215

(Dated: October 25, 2002)

We have developed and demonstrated a system capable of directly measuring the photon-number state of a pulse of light. We experimentally verify the photon-number distribution of a weak pulsed-laser source at 1550nm. Such single-photon metrology at telecommunication wavelengths provides the foundation for ensuring the security of photon sources used in implementations of quantum cryptography. This system has the lowest noise equivalent power of any single-photon detector and will enable secure quantum key distribution over distances greater than 100 km. Furthermore, this is the first system to combine the capability of counting photons over the full near-IR/visible/near-UV spectral bands with the ability to resolve multi-photon absorption events. These capabilities, combined with negligible dark count probability, allow this system to meet many of the essential requirements of the photon counters needed by scalable photonic quantum computing implementations.

PACS numbers: 03.67.-a,85.25.Oj,85.25.Pb

To satisfy the photon-generation requirements of the emerging field of quantum information technology, researchers have put increased effort into the development of true single-photon sources[1–3]. For example, the ultimate security of a quantum cryptography (or quantum key distribution) system based on single photon sources can be destroyed by a host of eavesdropping attacks if the source departs from ideal operation by emitting more than one photon in the same quantum-bit state. However, the security of quantum cryptography systems can also be compromised if the detectors used in the receiving system have high error rates[4, 5]. As a result, very low-noise single-photon detectors are also needed. Additionally, the realization of long-distance ($>$ 100 km) quantum cryptographic networks requires sources and detectors that operate at near-infrared wavelengths ($\lambda > 1.3\ \mu$m) to ensure a minimum of photon loss due to absorption in the optical fibers[6]. Conventional near-infrared detector systems are severely limited by low sensitivity and high dark-count rates[7–9] and cannot, even in principle, provide photon number-state discrimination, a capability essential for directly measuring the multi-photon error rate of a single-photon source. Finally, high-efficiency detectors with the capability of performing photon number-state determination with neglible dark count probability are required for implementations of linear-optics quantum computing[10]. Conventional detectors meet very few of the above requirements. In this letter we describe a system built to specifically address these issues and demonstrate the efficient measurement photon-number states at the ideal telecommunication wavelengths ($\lambda = 1310$ nm and 1550 nm) with negligible dark-count probability.

*Electronic address: Aaron.Miller@NIST.gov

Our system is based on the superconducting transition-edge sensor (TES) microcalorimeter technology originally developed for high-performance astronomical spectrophotometers[11]. The TES device produces an electrical signal proportional to the heat produced by the absorption of a photon. The increase in temperature of the absorber is measured by an ultra-sensitive thermometer consisting of a tungsten film with a very narrow superconducting-to-normal resistive transition ($T_c \sim 125$ mK, $\Delta T_c \approx 1$ mK). Applying a voltage across the metal film causes it to self-bias in the resistive transition allowing its temperature to be determined by measuring the electrical current flow through the metal. In this configuration the integral of the current pulse is proportional to the optical energy deposited in the absorber[12]. The tungsten devices are fabricated on a silicon substrate and are electrically connected with patterned aluminum wires. The tungsten acts as both the photon absorber and the thermometer and has an area of 25 μm$\times$25 μm and a 35 nm thickness. The superconducting aluminum wires ($T_c \approx 1$ K) are thermally insulating at the device operating temperature thereby ensuring that heat generated by the absorption of photons is confined to the thermometer.

The device is optically and electrically configured as shown schematically in Fig. 1. For the light source we use pulsed fiber-coupled lasers, visible or infrared, coupled to a single-mode fiber and then heavily attenuated. The light is coupled to the TES device at 125 mK using a telecommunications fiber-coupling ferrule by centering the end of the fiber over the detector at a distance of $\approx 125\ \mu$m. The sub-Kelvin operating temperature for the device is provided by a portable adiabatic demagnetization refrigerator[13]. The detector is voltage biased using a room-temperature current source ($I_{\rm bias}$) shunted through a small resistor ($R_{\rm b}$) at a temperature of 4 K. The device signal ($I_{\rm sense}$) is amplified by a 100-element series array of dc-SQUID amplifiers[14] at 4 K and finally processed with room-temperature pulse-shaping electronics. The rise and fall

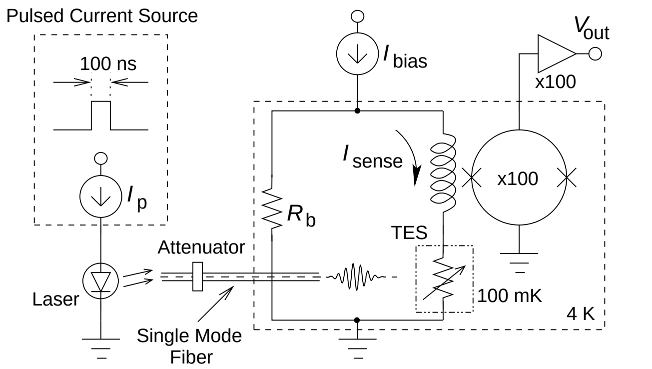

FIG. 1: Schematic of TES device biasing, readout and optical coupling. The optical source is a pulsed telecommunication laser (1310 or 1550 nm) coupled to a single-mode fiber. The pulses are attenuated with an in-line fiber attenuator and then coupled to the TES. The voltage bias for the device is provided by a room-temperature current source (I_{bias}) and a $100\ \mu\Omega$ shunt resistor (R_{b}) at 4 K. The device signal I_{sense} is amplified by a 100-element array of dc-SQUID amplifiers and processed with room-temperature pulse-shaping electronics.

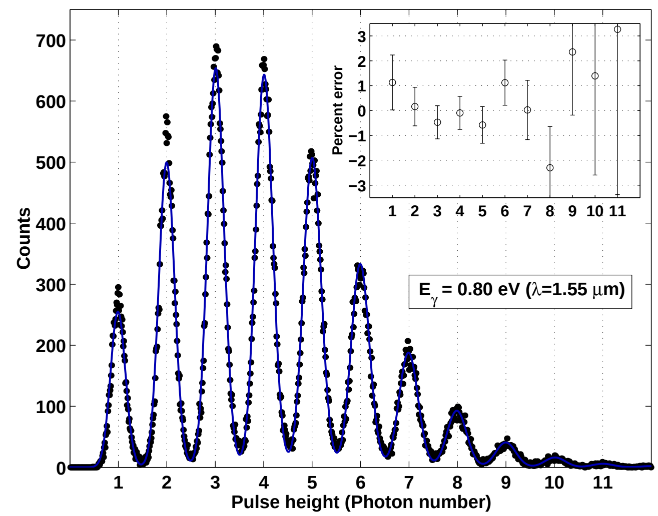

FIG. 2: Comparison of the measured pulse-height distribution of a pulsed-laser source using a TES calorimetric photon counter with the expected photon-number distribution. The source was 100 ns wide pulses of 1550 nm laser light at a repetition rate of 500 Hz containing an average photon number of $\mu \approx 4$. Total acquisition time was four minutes. Shown are the data (•) and best fit ($-$) Poisson distribution convolved with the measured device response. Inset shows the difference between measured and fit probability distributions. Error bars show the expected $\sqrt{N}$ standard deviation due to counting statistics.

times of the sensor are approximately 100 ns and $15\,\mu$s respectively, allowing event count rates up to 20×10^3 counts/s[15].

The optical efficiency of the device is determined by the intrinsic absorptivity of the W film, which gives a quantum efficiency (QE) of 40 to 50 $\%$ across the entire near-UV to near-IR band ($\lambda = 200$ nm-1800 nm)[11, 16]. The combination of moderate energy resolution and high quantum efficiency enables broadband spectroscopy to be performed down to the single-photon level. Conventional single-photon detectors, such as avalanche photodiodes or photomultiplier tubes, have little or no photon-number measurement ability due to the saturating avalanche-amplification process. In contrast, the output of an ideal calorimetric photon counter is proportional to nE_γ, where n is the photon number-state measured ($n = 1, 2, ...$) and E_γ is the single-photon energy ($E_\gamma = hc/\lambda$). Shown in dots (•) in Fig. 2 is the pulse-height distribution from our TES photon counter in response to a periodically gated $\lambda = 1550$ nm ($E_\gamma = 0.80$ eV) telecommunication laser attenuated to give an average of about 4 absorbed photons per gate interval. This interval is short enough (~ 100 ns) to ensure that the system counts multiple photons within each interval as a single energy-absorption event. The total acquisition time was 4 minutes with the source running at a repetition rate of ~ 500 Hz. These and similar data demonstrate that the response of the system is linear with photon number to within $5\ \%$ up to $n = 15$. In addition to $\lambda = 1550$ nm we have demonstrated photon counting at wavelengths (energies) of 670nm $(1.85$eV$)$, 830nm $(1.49$eV$)$, 1310nm $(0.95$eV$)$ with the photon-number discrimination ability improving at lower source wavelength (higher energy) because of the increased separation between adjacent photon-number peaks.

The pulsed-laser source measured here is typical of the weak coherent sources used in the implementations of quantum cryptography to date. In such sources the probability of producing an n-photon state $|n\rangle$ is a Poisson distribution $P(n) = (\mu^n/n!)e^{-\mu}$, where $\mu = \langle n \rangle$ is the mean number of photons per pulse[17]. The solid line in Fig. 2 is the result of a fit of the data to this Poisson distribution convolved with the energy resolution of the device (a Gaussian with standard deviation σ_E). The fit has a total of two free parameters and results in $\mu = 4.02 \pm 0.16$ and $\sigma_E = 0.120 \pm 0.017$ eV. The inset in Fig. 2 shows the difference between the measured distribution (integrated for each photon number) and the calculated $\mu = 4.02$ Poisson distribution. The two distributions agree to within the expected deviations due to photon-counting statistics (error bars show the expected 1-σ standard deviations).

The calorimetric measurement of energy-absorption events enables the detectors to have very low photon-counting noise with high intrinsic optical efficieny. False detector triggers are determined solely by the intrinsic 125 mK thermal fluctuations of the device. Assuming a Gaussian distribution appropriate for this type of thermal noise, the expected dark-count rate is less than 1 event per 1000 seconds, corresponding to a dark-count probability of lower than 10^{-10} per gate interval[18]. In addition to the negligible dark-count probability, we have demonstrated near-infrared detection efficiencies comparable to present technologies. Our measured absolute quantum efficiency is typically $20\ \%$ at 1310 nm and 1550 nm. The two main sources of loss are the fiber-to-detector alignment and the reflectivity of the tungsten devices. Through better alignment and the use of anti-reflection coatings on the detector[19] we expect to easily achieve efficiencies over 80%, a significant improvement over typical infrared photon-counter efficiencies of $20\ \ \%$ or less[7, 20, 21]. The common figure of merit that combines the dark-count rate and detection efficiency is the noise-equivalent power defined as $\mathrm{NEP} = (h\nu/\eta)\sqrt{2R}$, where $h\nu$ is the photon energy, η the detection efficiency, and R the rate of dark counts. Our measured values of $\eta = 20\,\%$ and $R = 1 \times 10^{-2}$ counts/s (limited by stray background light) give an NEP for our system below $1 \times 10^{-19}\,\mathrm{W/Hz}^{1/2}$, three orders of magnitude better than the best NEPs achieved with traditional telecommunication-wavelength photon counters and over one order of magnitude better than even the best silicon-based single-photon detectors can achieve at visible wavelengths[20].

It is now clear how this system can be used to quantitatively evaluate the security of emerging single-photon sources for use in secure quantum cryptography systems. A quantum communication channel can be compromised if the optical sources used in the system emit multiple photons instead of single photons[4, 5]. Significant progress has been made toward practical realizations of a single-photon source designed to specifically address this security loophole[1–3, 22, 23]. The non-Poisson behavior of these devices is typically observed in the second-order coherence of emitted light by use of two detectors in a Hanbury Brown-Twiss (HBT) configuration[17, 24]. Although very successful at allowing the characterization of non-Poisson sources at the two-photon level, the HBT configuration has a maximum theoretical efficiency of $50\,\%$ and cannot provide information about photon-number states with $n > 2$. Because all photon-number states can be directly measured with a single TES device, the full probability distribution for a source can be observed using just one channel of this system with no fundamental limit to the quantum efficiency. The measured distribution in Fig. 3 is an example of the photon number distribution of a weak-coherent pulsed-laser source with mean photon number per pulse of $\mu \approx 0.5$. This μ is characteristic of sources used in certain quantum key distribution implementations[25]. These data are shown on a semi-log plot to emphasize the clean number-state peak separation and near-Gaussian peak shape. From such distributions the rate of multi-photon (insecure) and single-photon (secure) pulses can be directly measured allowing photon sources to be unambiguously qualified for use in secure quantum networks. For a source with this photon-number distribution we determine the fraction of pulses that are insecure is 0.237 ± 0.002 consistent with a Poisson distribution with $\mu \approx 0.52$.

These detectors are exciting not only for their unique ability to perform characterization of low-flux sources, but also for the improvements they promise as receivers in quantum cryptography systems. The implementation of long distance (> 100 km) fiber-based quantum cryptographic networks requires sources and detectors that operate at near-infrared wavelengths ($\lambda > 1.3\ \mu$m) to signal degradation due to absorption and dispersion. The high efficiency and negligible dark-count rate of our system will enable unconditional secure key transmission over a distance of 100km using a source with a mean photon-number per pulse as high as $\mu = 0.001$[26]. With conventional detectors, the same assumptions allow unconditional security only over distances less than 40 km due to the high probability of recording a false detector trigger instead of a signal photon.

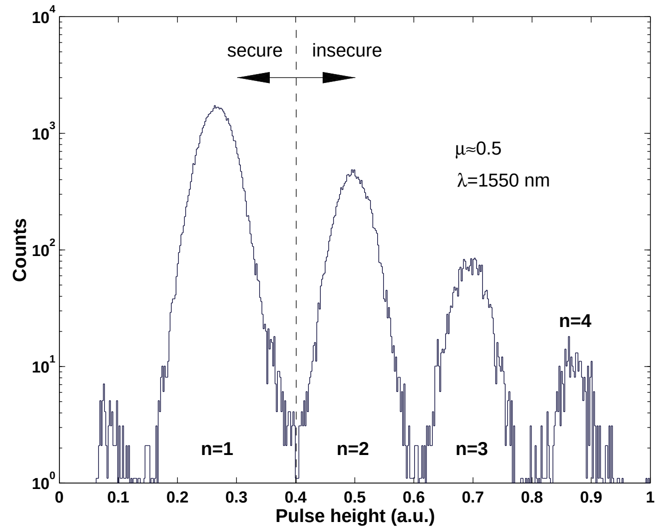

FIG. 3: Photon-number distribution of a weak coherent pulsed source with mean number of photons per pulse $\mu \approx 0.5$ and wavelength $\lambda = 1550$ nm. The quantum-cryptographically secure (single-photon) and insecure (multi-photon) events are indicated. Data are shown on a semi-log plot to accentuate the interpeak events. Note the clean separation between number-state peaks and the near-Gaussian peak shape.

The novel combination of low error-rate with the ability to perform true photon counting across the optical and infrared bands satisfies some of the challenging requirements for the advanced detectors needed for scalable photonic quantum computing implementations. The implementation of the linear-optics quantum computing (LOQC) scheme proposed by Knill *et al.*[10] uses only linear optical elements, single-photon sources, and photodetectors, though the proposed photodetectors have required capabilities that far exceed those of conventional detector technologies. Although our present photon-counting system was not designed to be fast enough nor efficient enough for use in a practical LOQC implementation, it is the first to meet the stringent noise and photon-number resolving criteria and may provide the basis for a system that meets all of the LOQC detector requirements.

Acknowledgments

This work was funded by grants from DARPA and NIST. We wish to thank Rich Mirin and Norm Bergren at NIST for valuable discussions and infrastructure assistance, the Stanford University group lead by Blas Cabrera for suppling the tungsten-coated wafers used in making these devices, and the NIST Cryogenic Sensors Project for the use of their cryostat.

[1] Z. L. Yuan, B. E. Kardynal, R. M. Stevenson, A. J. Shields, C. J. Lobo, K. Cooper, N. S. Beattie, D. A. Ritchie, and M. Pepper, Science **295**, 102 (2002).
[2] C. Santori, M. Pelton, G. Solomon, Y. Dale, and Y. Yamamoto, Physical Review Letters **86**, 1502 (2001).
[3] J. Kim, O. Benson, H. Kan, and Y. Yamamoto, Nature **397**, 500 (1999).
[4] G. Brassard, N. Lutkenhaus, T. Mor, and B. C. Sanders, Physical Review Letters **85**, 1330 (2000).
[5] J. Calsamiglia, S. M. Barnett, N. Lutkenhaus, and K. A. Suominen, Physical Review A **64**, 043814 (2001).
[6] G. Ribordy, J. Brendel, J. D. Gautier, N. Gisin, and H. Zbinden, Physical Review A **63**, 012309 (2001).
[7] J. G. Rarity, T. E. Wall, K. D. Ridley, P. C. M. Owens, and P. R. Tapster, Applied Optics **39**, 6746 (2000).
[8] P. C. M. Owens, J. G. Rarity, P. R. Tapster, D. Knight, and P. D. Townsend, Applied Optics **33**, 6895 (1994).
[9] Detectors for optical wavelengths have been developed that are capable of photon number-state discrimination. However, they have high dark-count rates and are not sensitive at telecommunication wavelengths. See, for example, Ref. 27.
[10] E. Knill, R. Laflamme, and G. J. Milburn, Nature **409**, 46 (2001).
[11] R. W. Romani, A. J. Miller, B. Cabrera, S. W. Nam, and J. M. Martinis, Astrophysical Journal **563**, 221 (2001).
[12] K. D. Irwin, Applied Physics Letters **66**, 1998 (1995).
[13] D. A. Wollman, K. D. Irwin, G. C. Hilton, L. L. Dulcie, D. E. Newbury, and J. M. Martinis, Journal of Microscopy-Oxford **188**, 196 (1997).
[14] R. P. Welty and J. M. Martinis, IEEE Transactions on Magnetics **27**, 2924 (1991).
[15] B. Cabrera, R. M. Clarke, P. Colling, A. J. Miller, S. Nam, and R. W. Romani, Applied Physics Letters **73**, 735 (1998).
[16] R. W. Romani, A. J. Miller, B. Cabrera, E. Figueroa-Feliciano, and S. W. Nam, Astrophysical Journal **521**, L153 (1999).
[17] R. Loudon (Oxford University Press, 2000), 3rd ed.
[18] In practice the dark-count rate will most likely be limited by factors such as stray light scattering into the optical path or unknown sources such as fluorescence. Of course, this is not an intrinsic detector limitation and can be mitigated by proper spectral filtering.
[19] M. Rajteri, M. L. Rastello, and E. Monticone, Nuclear Instruments & Methods in Physics Research Section A-Accelerators Spectrometers Detectors and Associated Equipment **444**, 461 (2000).
[20] I. Prochazka, Applied Optics **40**, 6012 (2001).
[21] P. A. Hiskett, G. S. Buller, A. Y. Loudon, J. M. Smith, I. Gontijo, A. C. Walker, P. D. Townsend, and M. J. Robertson, Applied Optics **39**, 6818 (2000).
[22] P. Michler, A. Kiraz, C. Becher, W. V. Schoenfeld, P. M. Petroff, L. D. Zhang, E. Hu, and A. Imamoglu, Science **290**, 2282 (2000).
[23] P. Michler, A. Imamoglu, M. D. Mason, P. J. Carson, G. F. Strouse, and S. K. Buratto, Nature **406**, 968 (2000).
[24] R. H. Brown and R. Q. Twiss, Nature **177**, 27 (1956).
[25] R. J. Hughes, G. L. Morgan, and C. G. Peterson, Journal of Modern Optics **47**, 533 (2000).
[26] The assumptions made for this estimate are those of Ref. 4 with $\mu = \alpha^2 = 0.001$, detector efficiency $\eta_{\rm B} = 0.2$, a conservative dark-count probability bit-arrival interval $d_{\rm B} = 1 \times 10^{-8}$ for the TES devices and $d_{\rm B} = 5 \times 10^{-6}$ for conventional devices, a constant 5dB of optical losses in the receiver, and fiber losses of 0.2 dB/km at a transmission wavelength of 1550 nm. It should be noted that our assumed $\mu = 0.001$ is significantly lower than is typically used in existing quantum cryptography implementations due to our requirement that the system be unconditionally secure against even the strongest individual-bit eavesdropping attacks[4].
[27] J. S. Kim, S. Takeuchi, Y. Yamamoto, and H. H. Hogue, Applied Physics Letters **74**, 902 (1999).